NUMERICAL MODELING OF STATIC & DYNAMIC BEHAVIOR OF ELASTOPLASTIC SOILS

Ph.D. Dissertation

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Summary

This dissertation describes the formulation of a new numerical methodology for the modeling of the static and dynamic behavior of elastoplastic soils. The proposed methodology aims at simulating the soil response of non-cohesive soils under small, medium and large strains, with a single soil-specific set of constants, independent of soil density, stress level and loading conditions. Special emphasis is given to the simulation of the dynamic behavior and especially of earthquake-induced liquefaction phenomena, without loss of accuracy in monotonic loading. On the contrary, both types of loading are treated equally by adopting the unified framework of soil response of Critical State Soil Mechanics (Roscoe & Burland, 1968).

The new model is a bounding surface plasticity model with a vanished elastic region and is based on a recently proposed constitutive model, which has been developed at the Geotechical Division of N.T.U.A. (Papadimitriou et al. 2001, Papadimitriou & Bouckovalas 2002). The non-linear soil response under small to medium cyclic strain amplitudes is simulated by introducing a Ramberg-Osgood-type hysteretic formulation in a manner similar to the paraelastic theory of Hueckel & Nova (1979). At large cyclic strain amplitudes elastoplasticity governs the behavior and a properly defined scalar-valued variable is introduced, which

reflects macroscopically the effect of fabric evolution during shearing on the plastic modulus.

In its current form, the model incorporates three open cone-type surfaces with apex at the origin of stress space:

(a) the Critical State surface at which shear deformation develops under constant stresses and volume,

(b) the Bounding surface which locates the peak stress ratio states, and

(c) the Dilatancy surface which divides the stress space into the areas where the soil dilates or contracts under shear loading.

These surfaces are interrelated via the state parameter ψ (Been and Jefferies, 1985), which quantifies the distance from Critical State in the effective stress – void ratio space. This procedure implements Critical State Theory in constitutive relations and allows for the simulation of response for all stress levels and void ratios with the same set of model constants.

The proposed model has no purely elastic region and thus the response of soil during loading is continuously elastoplastic, i.e. irrecoverable deformations occur at every incremental step. The choice of a vanished elastic region provides a smoother transition from small to large strains and hence improves the numerical robustness and efficiency of the code. In this way, it was possible to satisfactorily resolve a number of issues that significantly increase the required computational effort, i.e. the stress point crossing of the yield surface and the drift correction resulting from the weak enforcement of the consistency condition.

The foregoing adoption of a vanished yield surface differentiates the proposed model from the original (Papadimitriou, 1999), since it lead to a number of other modifications as well, namely: (i) the introduction of a new mapping rule of the current stress to its conjugate on the Bounding surface and (ii) the modification of the existing interpolation rule that relates the current value of the plastic modulus to that on its conjugate state.

This new constitutive model was implemented in the commercial 2D finite difference code FLAC (Itasca 2005). This code is oriented towards problems of Geotechnical Engineering and provides the option for implementing new constitutive models via external subroutines (User Defined Model option) that update the stresses for any given strain increment. Emphasis was given to the stress integration procedure, where the sub-stepping technique with automatic error control proposed by Sloan et al. (2001) was adopted. It belongs to the family of effective explicit algorithms, and divides automatically the applied strain increment into sub-increments, using an estimate of the local error. A modified Euler scheme is used, which consists of two basic steps.

In the present study, the parameters of the model are calibrated on the basis of data from element laboratory tests performed on fine Nevada sand at relative densities of Dr = 40 & 60% and initial effective stresses between 40 and 160 kPa (Arulmoli et al. 1992). In particular, the data originate from resonant column tests as well as direct simple shear and triaxial tests. Thus, they offer a quantitative description of various aspects of non-cohesive soil response under cyclic loading, such as shear-modulus degradation and damping increase with cyclic shear strain, liquefaction resistance and cyclic mobility.

The ability of the proposed numerical methodology to simulate real boundary value problems has been validated, by comparing numerical predictions against centrifuge results from the well-known VELACS experimental project (Arulmoli et al. 1992). On that purpose, three different problems of Geotechnical Earthquake Engineering were simulated, namely:

(a) *Test No. 1* that simulates the one – dimensional (1-D) response of a liquefiable soil layer under level conditions

(b) *Test No. 2* that simulates the response of a mildly sloping liquefiable soil layer (lateral spreading)

(c) *Test No. 12* which simulates the response of shallow foundations on liquefiable soils

Although the simulated problems correspond to three different situations, they were predicted with quantitative accuracy, using a single soil-specific set of constants, which was computed during the calibration procedure.

During the validation procedure, the significance of soil permeability on the results was highlighted. Data from laboratory tests have shown that the value of permeability changes during the initial liquefaction of the subsoil, due to changes in the soil structure. This phenomenon was simulated.

Furthermore, specific directions for future research are provided, aiming at improving the proposed model and generalizing the numerical methodology for simulating three – dimensional boundary value problems.